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Around the globe, governments have pledged to remove support for coal, oil, and gas,, noting that such fossil fuel subsidies "undermine efforts to deal with climate change" by keeping greenhouse gas emissions higher than they otherwise would be.[1] Jewell *et al.* used results of integrated assessment models to infer that eliminating subsidies would yield "limited emissions reductions … except in energy-exporting regions," and described the emission reduction benefits as "small."[2] This characterization is potentially misleading, and we use a simple, sector-specific model to show how the emission reductions from producer subsidy reform could be more material than Jewell *et al.* suggest.[3] Fossil fuel producer subsidies delay a low-carbon transition in ways both material and political, and they deserve greater attention and transparency in global modeling analyses, as well as in policy-making.

The study by Jewell *et al.* provides important findings related to fossil fuel subsidy removal. Using a synthesis of five Integrated Assessment Models (IAMs), they find that subsidy removal could reduce global emissions by 0.5 to 2 gigatons (Gt) carbon dioxide (CO_2) by 2030.[2] Jewell *et al.* characterize these global emission reductions as "unexpectedly small," while noting they would largely occur within a few energy-exporting countries and regions (Russia, the Middle East, and Latin America).

We argue that the emissions reductions from subsidy removal are not small. By contrast, 0.5 to 2 Gt CO_2 amounts to roughly one quarter of the energy-related emission reductions pledged by all countries under the Paris Agreement (4 to 8 Gt CO_2) – all from a single policy approach that also comes with strong fiscal and other environmental benefits.[4] This scale of emission reductions should not necessarily be surprising or unexpected: few policy analysts place their hopes on *any* single instrument to deliver reductions at the scale needed to meet climate goals.

Moreover, we argue that the impact of subsidy removal on emissions is likely to be more significant than Jewell *et al.* find, particularly when considering support for fossil fuel *producers* in high-income countries. Although Jewell *et al.*'s approach uses common IAM techniques, it does not adequately capture investment dynamics in the supply of new fossil fuels, and therefore misses a major pathway for subsidy reform to affect CO_2 emissions. Specifically, their approach does not consider how the timing of producer subsidies (concentrated early in an investment lifetime) and the higher effective discount rates of investors (as compared with society) affect investment decisions to bring on new supplies of oil.

Oil provides more of the world's energy than any other fuel, and exploration and development of supplies remain robust.[5] Jewell *et al.* model producer subsidies to oil by distributing regional subsidy totals equally to all oil fields – new and already-producing fields alike -- in each region, proportionate to annual output. But that is not how subsidies to oil producers often work. Instead, governments often target subsidies more toward new capital investment than ongoing production. By lowering upfront cash flow requirements, government subsidies boost project investment metrics (such as rate of return or net present value), which leads producers to drill more new wells than they would otherwise. This locks in higher future fossil fuel production and, in turn, consumption, and greenhouse gas emissions.[6]

Using the example of one type of subsidy for investment – accelerated depreciation of new capital investment – we illustrate how oil subsidies could have a bigger effect on global CO_2 emissions than in Jewell et *al.*'s analysis. This particular form of support, exemplified by the "intangible drilling cost" (IDC) subsidy in the United States, allows companies to quickly write down capital investments that would otherwise depreciate more gradually, providing a boost to cash flow at the beginning of a project.

The IDC subsidy is underappreciated in Jewell *et al.*'s analysis because they value it only at the reported value of about USD_{2016} 0.20 per barrel.[7] This reflects the reduction in cash flow to the US Treasury that results from the delay in annual tax payments. But while the US government may be almost indifferent whether they receive tax revenues this year versus the next, oil company investors are not – they can use that cash flow to accelerate new investment.

If the IDC were valued not on a nominal cash basis but instead on a present value basis, using investor discount rates of 10 to 20%, the subsidy would make it substantially easier to invest in new oil fields, decreasing the breakeven oil price of new projects by USD_{2016} 4 to USD_{2016} 7 per barrel (Table 1).

Changes in breakeven economics of this scale could have a substantial effect on global oil market price dynamics and consumption. This would especially be the case if subsidy removal were to render uneconomic many of the new projects on course to be developed before 2030. This outcome could well arise, since the US has a substantial fraction (more than 40%) of the new oil projects that can be produced by 2030 (Extended Data Figure 1). Other producers with substantial new supplies planned, such as Canada[9] and Norway[10], also offer accelerated depreciation of new oil capital investments.

Table 1 estimates how the global oil market may respond to removal of the accelerated depreciation subsidies, based on a simple oil market model (see *Methods*). As shown, in the low oil price world featured by Jewell *et al.*, the effect of removing the depreciation subsidy to producers could reduce global oil consumption by 440 to 770 million barrels in 2030.

Yet Jewell *et al*.'s analysis includes only a very small fraction of this effect. They do not report this result, but we estimate it to be roughly 21 million barrels (Table 1, column A).

We therefore believe that, in their low oil price case, Jewell *et al.* missed a reduction in global CO_2 emissions from oil combustion on the order of 200 to 300 million tons CO_2 that could result from the removal of a single type of subsidy common in the US and other oil-producing countries.

The actual outcome on *net* global CO_2 emissions from all fuels is likely to be somewhat lower because coal or gas might substitute for some of the lost oil consumption, though concurrent removal of subsidies for these fuels would minimize this effect. IAM models, like those used by Jewell *et al.*, are well suited to evaluating these interactions. Yet the scale on which CO_2 emissions from oil have potentially been underestimated – equivalent to 10% to 60% of Jewell *et al.*'s reported global effect due to removal of *all* subsidies (0.5 to 2 Gt CO_2 in 2030) – suggests that oil producer subsidies deserve greater attention and transparency in global modeling analyses.

The investment-oriented approach to modeling subsidies used here and the broader, average cost-curve approach of Jewell *et al.* are not incompatible. Fossil fuel supply in IAMs could be modeled using an investment approach and vintage capital structure, as is commonly applied to power plants that have up-front costs and default lifetimes.[8] In such an approach, new oil deposits would also be modeled as prospective investments, using realistic discount rates of 10% to 20% that are common in the oil industry and demonstrated here.

In fact, subsidies may play an even more important role than we can quantify here. Extra company revenue resulting from subsidies can be used not only for more drilling, but also for product promotion, political activities, and other efforts that fortify the industry's incumbent status. Subsidies also have a symbolic effect, in that they communicate the normative position that this industry and its activities are beneficial for society as a whole and, therefore, should be encouraged. Jewell *et al.* disregard these socio-political effects when downplaying the value of removing fossil fuel subsidies.

The economic, political, and symbolic effects of subsidies reinforce each other.[13] For example, subsidies can beget more subsidies, with new, long-lived fossil fuel infrastructure in turn (a) requiring further subsidization down the line to continue operating,[14,15] and (b) yielding beneficiaries who will vigorously defend continued subsidization.[16] Since there can be a revolving door between government staff and subsidy recipients, public officials may find it even harder to pass strong climate and energy policies.[17] Indeed, the most troubling impact and legacy of fossil fuel subsidies may be the political barriers that fossil fuel producers have erected in recent decades against decarbonisation efforts.[18,19]

Rapid low-carbon transitions consistent with the guardrails of the Paris Agreement require dramatically reduced fossil fuel production.[20] Subsidies to fossil fuel companies pose formidable financial, institutional, and political obstacles to this transition, impeding the efficacy of greenhouse gas emission reduction strategies. The apparent small dollar values of producer subsidies in official, government-approved ledgers – and the limited emissions impact suggested by global models such as those used by Jewell *et al.* – can be misleading. The actual impacts, particularly when one takes into account their social and political impacts, are far greater.

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Author contributions

P.E. and M.L. conceptualized the research with input from H.v.A., D.K., N.O., and G.S. P.E. carried out the numerical modeling. P.E. wrote and revised the manuscript with contributions from H.v.A, D.K., M.L., P.N., N.O., and G.S.

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Table legend

Table 1: Subsidies allowing accelerated write-down of capital investment can reduce the breakeven price of new oil projects by USD 4 to USD 7 per barrel, depending on investor hurdle rate. These estimates are calculated on a present value basis, as the production-weighted averages across nearly 800 discovered oil fields in the United States (See *Methods* section). By contrast, Jewell *et al*. value the fast depreciation subsidy only on a cash basis, spread across all fields; while they do not report the value of this subsidy in their analysis, we estimate it from the same primary sources they used to be about USD 0.20 per barrel (column A), as described further in the *Methods* section. We estimate the market effects of removing these subsidies using a simple oil market model, at three different investor discount rates (columns B-D), all of which are on a nominal basis (no deduction for inflation). We assume that not-yet-developed US oil projects are higher up the oil cost curve in 2030 (as is oil from other countries that also have a corresponding accelerated depreciation subsidy, like Canada or Norway), such that increases in the breakeven prices of these fields could well have a direct effect on long-term prices and consumption levels. We also assume here that subsidy removal begins immediately (i.e., in 2019), whereas Jewell *et al*. assume subsidy phase-out starts in 2020 and is completed in 2030. However, producer subsidy removal is not subject to the same concerns as consumer subsidy removal – namely equity and locked in consumer behavior – and thus would not need to be phased in so gradually.

Methods

Our analytical contribution is to show how different approaches to valuing fast depreciation subsidies for new oil fields may yield very different outcomes for global oil consumption and resulting CO_2 emissions from burning this oil. There are three main steps to the analysis presented in Table 1.

The first step, with results shown in the first row of Table 1, is to estimate how much two different subsidy valuation approaches affect the breakeven oil price needed for new oil supply investments to proceed. In one approach, adopted by Jewell *et al*. and confirmed by correspondence with Dr. Jewell in November 2018, oil production subsidies are valued by taking government- reported subsidy values (compiled by the OECD) and spreading them across all oil production in the given region. For the intangible drilling cost subsidy in the US – used here as the example of a fast depreciation subsidy – the reported value in 2013 and 2015 (years that Jewell et al. use to represent their high and low oil price cases, respectively) were USD 550 million and USD 660 million. Updating these values to USD2016 dollars using the World Bank Development Indicators[21] and normalizing for US oil production in 2013 and 2015 years of 2.7 billion and 3.4 billion barrels[22] yields about USD2016 0.20 per barrel in either price case.

To value subsidies instead using the present value approach of investors, we start with field-level data on capital investment, operating costs, taxes, and production profiles for nearly 800 discovered but not yet developed (as of mid-2016) oil fields in the US. These are the same fields analyzed by Erickson *et al.* 2017, though we analyze them here anew, using the same cost and production assumptions as in that original analysis, including for tax rules. (We maintain such original assumptions unchanged, to accurately represent a point in time, recognizing that some factors may have since changed, including the corporate tax rate in the US.) Starting with the field-level data, we then calculate how the intangible drilling cost subsidy would affect cash flows for each field and, in turn, the levelized net present value (NPV) for each project under three different investor discount (hurdle) rates: 10%, 15%, and 20%. We select these three hurdle rates (all of which are on a nominal basis, with no discounts for inflation) to represent hurdle rates common in the academic literature (10%) and investor literature (15%), as well a rate (20%) that represents a weakened, higher risk investor climate, just as Iyer *et al.* do for a different sector,[23] and as is already being observed in some parts of the US oil industry.[24] The results of this exercise are presented as averages (production-weighted across all 800 fields) in columns B-D of the first row of Table 1

The second step in our analysis is to model the effect of removing subsidies on global oil price and consumption using a simple oil market model, parameterized by elasticities. Assuming, in the long run, that the oil market behaves as a single global market, basic microeconomics indicates that, for small increases in producer costs (here, resulting from subsidy removal), $d\tau$, the resulting change in oil price, dP, can be approximated according to the following equation, where E_s and E_d are elasticities of supply and demand, respectively.[25]

$$dP \approx \frac{E_s}{(E_s - E_d)} d\tau \qquad (1)$$

The choice of elasticities therefore determines the changes in price, e.g. presented in Table 1 of the main text.

Elasticities are not uniform; they depend on the oil price environment. For example, at very high oil prices, the oil supply curve is generally understood to be much steeper (fewer barrels of new oil supply available for each increment in oil price, i.e. low elasticity of supply) than at lower prices.

We therefore adapt high and low oil price cases from Figure 1 of Jewell *et al.* to parameterize our simple oil market model (Equation 1 above). Specifically, we use their median values in 2030, denominated there in 2005 prices, and update them to 2016 prices following the World Bank's World Development Indicators consumer price index.[21] This process yields a high oil price case of USD_{2016} 170 per barrel and a low oil price case of USD_{2016} 70 per barrel. We focus mainly on this low oil price case in the text, much like Jewell *et al.* do, as USD2016 70 per barrel is much closer to the current price of oil and also to the long-term price of oil consistent with actions, such as may be taken under the Paris Agreement, to limit oil demand.

To derive elasticities associated with these oil price cases, we look to an oil supply curve from Rystad Energy,[26] widely used by the International Energy Agency and academic researchers, which shows large quantities of oil available at very low prices, especially from the Middle East where the supply curve is very "flat" (high elasticity), and steadily getting steeper at higher prices as new supplies become more costly. (A simplified version of this curve is included as Extended Data Figure 1.) At USD_{2016} 70, we calculate an elasticity of supply of 0.6, and at USD_{2016} 170, we calculate an elasticity of supply of 0.1. This range is in broad agreement with a review conducted by the OECD.[27]

For elasticities of demand, we assume that under the high oil price case, elasticity of demand is -0.2, consistent with other studies, and noting high uncertainty.[28–30] For the low oil price case, we assume a somewhat higher elasticity of demand, -0.3, under the assumption that it is lower-than-expected demand that could enable this low oil price case (e.g., due to faster-than-expected penetration of electric vehicles) and that the resulting greater consumer choice among fuels would result in a higher elasticity of demand, albeit one that is still conservative, as even higher values of -0.5 are common.[30] Elasticities of oil demand with respect to price of -0.2 to -0.3 are within the ranges for all five models reported in Supplementary Table 2 of Jewell *et al*., and are therefore considered here to be representative of the types of oil demand responses that those models would yield.

Together, using the equation above, these assumed elasticities imply that in the high oil price case, each dollar of increase in producer cost per barrel translates into an increase in global crude price of 0.33 dollars per barrel, whereas under the low oil price case, each dollar of increase in producer cost translates into an increase in the global crude price of 0.66 dollars per barrel. Applying these findings to the breakeven oil price effects from step 1, above, yields the increases in global oil prices reported in each column of Table 1.

Further, estimating how these changes in price would lead to changes in global oil consumption is then straightforward, using the elasticity of demand, E_d, which is defined as the percent increase in demand as a function of the percent increase in price. Assuming that in the high oil price case, global oil consumption is 46 billion barrels per year, and under the low oil price case is 37 billion barrels per year (see Extended Data Figure 1, which shows these as approximately the oil production levels at USD_{2016} 70 and USD_{2016} 170, respectively), a 0.33 dollar increase in oil price in the high oil price case translates via the elasticity of demand into a drop in global oil consumption of 18 million barrels per year, and a 0.66 dollar increase in oil price in the low oil price case translates into a drop in global oil consumption of 110 million barrels per year.

Lastly, for the third and final step, we convert barrels of oil to CO_2 emissions using the basic carbon content of a barrel of oil, about 0.4 t CO_2 per barrel.[29,31]

Methods references

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Extended data legends

Extended Data Figure 1. Cost curve of world oil production in 2030. Figure shows cumulative supply of oil in 2030 at increasing oil price. Most blocks (64) in this cost curve represent a combination of particular stage of development (four stages) in major world regions (eight: the continents plus Middle East and Russia minus Antarctica), whether onshore or offshore.

Further blocks represent the United States and Canada, since they are major new sources of oil, about 41% and 7% of all not-yet-producing oil in this figure. Figure adapted from Erickson, P. Confronting carbon lock-in: Canada's oil sands. (Stockholm Environment Institute, 2018) and based on data from Rystad Energy.

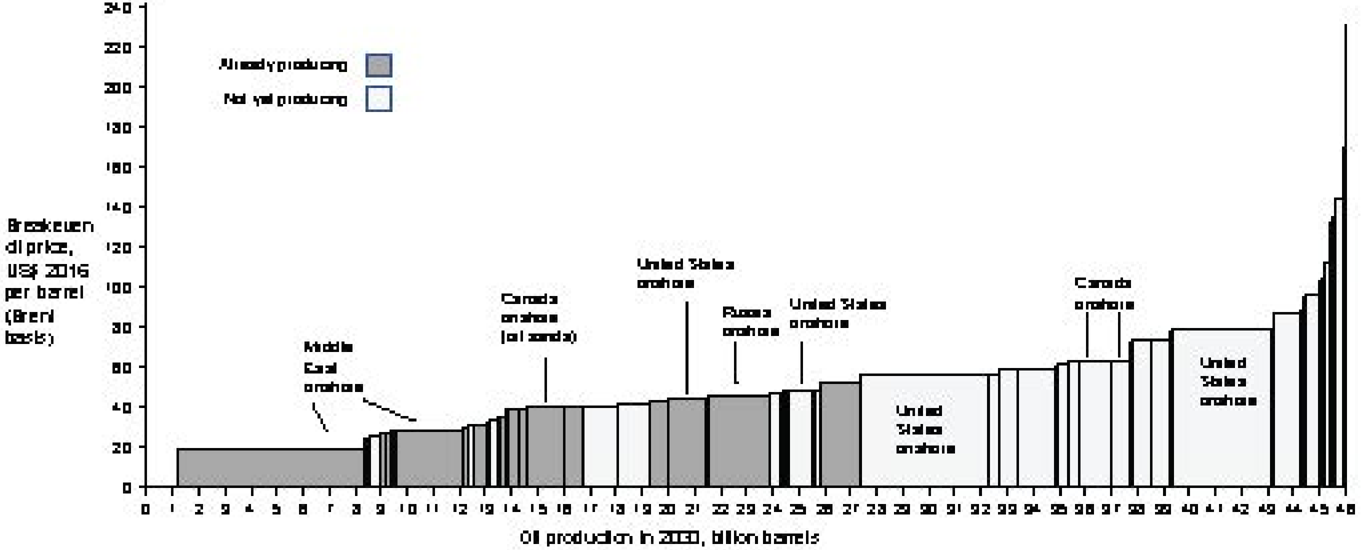
Data availability

The authors declare that data supporting the calculations in columns B through D of Table 1 are included as online supplementary information. The raw data analysed by the authors for Extended Data Figure 1 are available from Rystad Energy in their UCube database, but restrictions apply to the availability of these data, which were used under license for the referenced study, and so are not publicly available. Raw data are available from the authors upon reasonable request and with permission of Rystad Energy.

Code availability

No custom code or mathematical algorithms were used to generate results reported in this paper. The entirety of the oil market model is provided as equation 1 in the Methods section.

	(A) Subsidy valued on cash basis, as in US government source used by OECD and Jewell *et al.*	Subsidy valued on present value basis, at range of investor discount rates		
		(B) Rate common in academic literature	(C) Rate common in industry studies	(D) Higher-risk rate (if weakened investor climate or higher-risk fields)[8]
		10%	**15%**	**20%**
Effect of subsidy on economics of new oil projects				
Effect on projects' breakeven price (USD_{2016}), per barrel	0.20	4.20	5.80	7.30
Market effects of subsidy removal, high oil price case, 2030				
Increase in global oil price (USD_{2016}), per barrel	0.07	1.40	1.90	2.40
Decrease in global oil consumption (million barrels)	4	76	110	130
Decrease in global CO_2 emissions from oil, million t CO_2	1	30	42	52
Market effects of subsidy removal, low oil price case, 2030				
Increase in global oil price (USD_{2016}), per barrel	0.13	2.80	3.90	4.90
Decrease in global oil consumption (million barrels)	21	440	620	770
Decrease in global CO_2 emissions from oil, million t CO_2	8	180	250	310


Already producing
Not yet producing
Breakeven oil price, US$ 2016 per barrel (Brent basis)
Middle East onshore
Canada onshore (oil sands)
United States onshore
Russia onshore
United States onshore
United States onshore
Canada onshore
United States onshore
Oil production in 2030, billion barrels